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Growth and Mortality of Ponderosa Pine Poles Thinned to Various Densities in the Blue Mountains of Oregon

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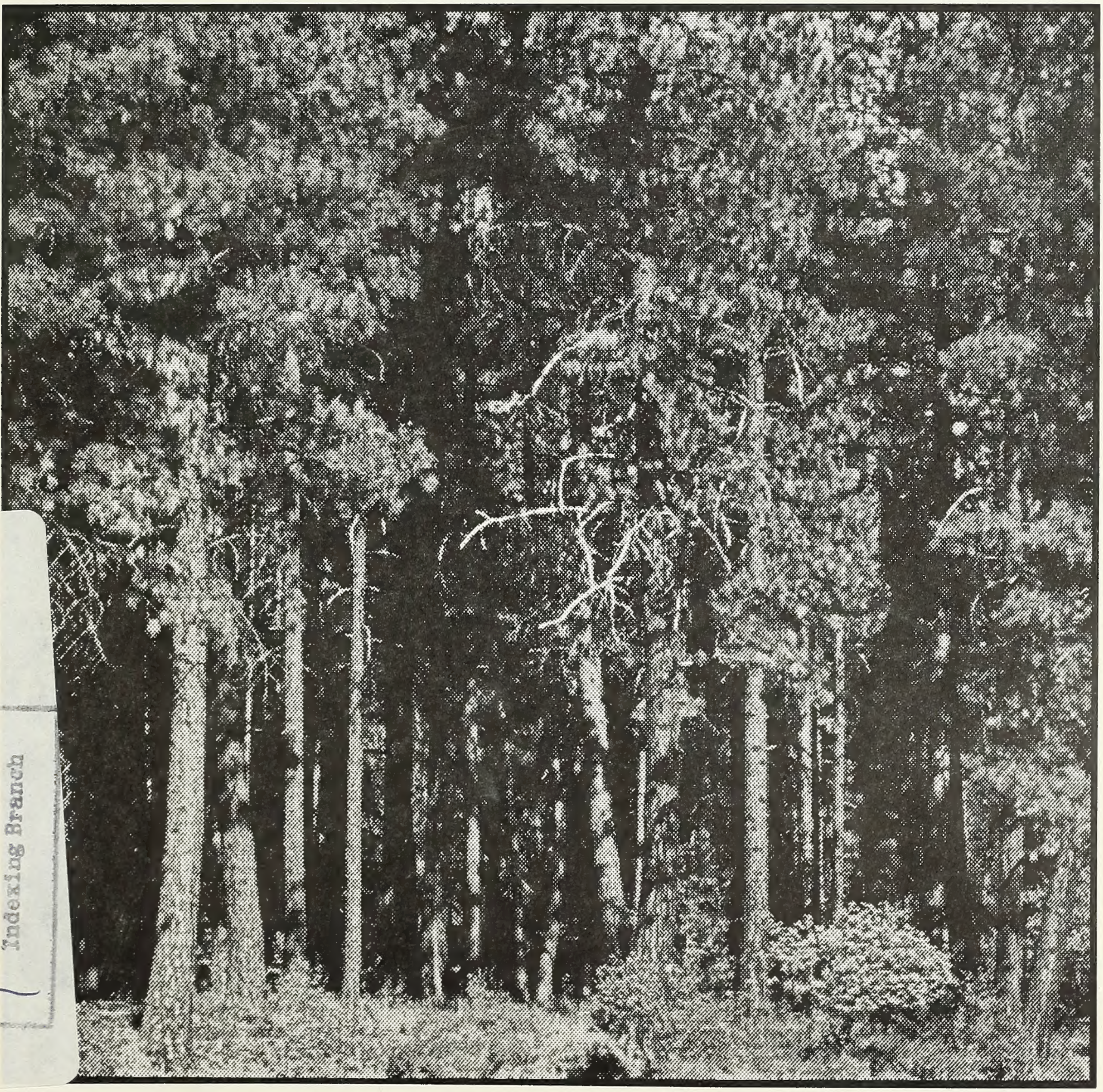

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Abstract

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Growth and mortality in a ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stand were investigated for 24 years. High mortality rates from mountain pine beetle (*Dendroctonus ponderosae* Hopkins) occurred on some plots where values for stand density index exceeded 140. Periodic annual increments for quadratic mean diameters decreased curvilinearly as stand density increased, whereas periodic annual increments of gross basal area and gross cubic volume increased curvilinearly with increasing stand density. Cubic volume yield at a stand age of 84 years increased linearly with increasing density. Mean annual increments of board foot volume increased with time and show no signs of leveling off at a stand age of 84 years. Mean annual basal area and volume growth of the 30 largest trees per acre decreased with increasing levels of stand density. Ponderosa pine on low sites should be managed at low stand densities to avoid problems with mountain pine beetle and to produce large trees in a reasonable time period. Long rotations are probably possible for this species.

Keywords: Growth, mortality, mountain pine beetle, ponderosa pine, Blue Mountains (Oregon), forest health, thinning.

Summary

Growth and mortality for six growing stock levels (GSLs) in a ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) pole stand on the Malheur National Forest were investigated for 24 years. Soils and vegetation of the study area occur over much of the Blue Mountains in northeastern Oregon and southwestern Washington. Plots were thinned initially and again at the end of the 10th and 19th growing seasons. The first two thinnings reduced the plot densities to prescribed basal areas (PBAs) defined in a westwide study plan (Myers 1967), and the third thinning reduced plot densities to values of stand density index (SDI) equivalent to SDI values of the original PBAs when the quadratic mean diameter (Dq) was 10 inches. High mortality rates from mountain pine beetle (*Dendroctonus ponderosae* Hopkins) occurred on some plots where SDIs were slightly above 140, little more than 40 percent of the normal value of 365. Gross periodic annual increments (PAIs) for basal area and volume increased curvilinearly as GSL increased. The PAIs for Dq, determined for surviving trees, decreased curvilinearly as GSL increased. The PAIs for average height, also determined for surviving trees, varied erratically with GSL. Net PAIs for basal area and volume varied erratically with GSLs because of mortality. All PAIs changed with period or stand age, and all PAIs except those for survivor heights generally at first increased and then decreased as stand age changed from 60 to 84 years. Mean annual gross cubic volume growth during the 24-year period increased curvilinearly with increasing GSL. Mean annual basal area and volume growth of the 30 largest trees per acre decreased with increasing GSLs. Cubic volume yield at a total stand age of 84 years increased linearly with increasing GSL. Scribner board foot yield was lower for both the lowest and highest GSLs than for the intermediate GSLs because of the relation of board foot volume to both cubic volume and tree size. The lowest GSL had the lowest cubic volume, and the highest GSL had the smallest tree sizes. Mean annual increments (MAIs) of cubic and board foot volume increased with time. Cubic foot MAIs for GSLs of 80 and above and all board foot MAIs showed little indication of leveling off at a stand age of 84 years. These results indicated that ponderosa pine on low sites should be managed at low stand densities to avoid serious mortality from mountain pine beetle and to produce large trees in a reasonable time. Long rotations may be possible for this species.

Introduction

Stocking level profoundly affects stand development, an important factor in all aspects of forest management. The relation of growth and mortality to growing stock retained in stands of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) repeatedly thinned to a wide range of stocking levels is under investigation at six locations in the United States (Myers 1967, Oliver and Edminster 1988). Two of these levels-of-growing-stock studies are in the Black Hills of South Dakota, two are in Oregon (Barrett 1983), one is in northern Arizona (Ronco and others 1985), and one is on the west slope of the Sierra Nevada in California (Oliver 1979).

These 24-year results for the levels-of-growing-stock installation on the Malheur National Forest in Oregon include five measurement periods, four having five growing seasons and one having four growing seasons. Stand conditions, plant associations, and soils similar to the study area occur over much of the Blue Mountains in northeastern Oregon and southeastern Washington as well as elsewhere in the intermountain West. Results of this study, therefore, should be applicable over a wide area.

Methods of Study

Study Area

Plots are 17 to 20 miles northeast of Prairie City, Oregon, T. 11 S., R. 35 E., secs. 11, 12, 14, 15, 22, 26, and 27, Willamette Meridian. Elevation is 4,400 feet, slopes range from 6 to 29 percent, and aspects in all quadrants occur. Much of the average annual precipitation of 21 inches is snow, often accumulating to depths of 2 feet. July, August, and September are dry with warm days and cold nights (Franklin and Dyrness 1988).

The area has one overstory, two understories, and three soils. The overstory consists primarily of ponderosa pine with some western larch (*Larix occidentalis* Nutt.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). One understory-soil combination is in the ponderosa pine/Idaho fescue (*Festuca idahoensis* Elmer) plant association (Hall 1973, Johnson and Clausnitzer 1991). The soil has a 6- to 10-inch loam surface with 12- to 45-percent gravel and cobbles over a loam subsoil having 35- to 65-percent gravel and cobbles. The second understory is in the Douglas-fir/elk sedge (*Carex geyeri* Boott) plant association (Johnson and Clausnitzer 1991). The associated soil has a 10- to 15-inch clay loam surface with 10- to 40-percent gravels and cobbles over a clay loam subsoil with 20- to 50-percent gravel and cobbles. This understory, which has a pine grass (*Calamagrostis rubescens* Buckl.) component, also occurs on a similar subsoil capped with a 6- to 12-inch layer of silt loam derived from Mazama ash typical of the mixed-conifer/pinegrass-ash soil association (Hall 1973). Total depth for all three soils ranges up to 72 inches.

Before study establishment (fall 1967), the overstory was a natural 60-year-old stand averaging 2,129 trees per acre with 178.5 square feet per acre of basal area and a quadratic mean diameter (Dq) of 3.9 inches. This density is about 11 percent higher than normal stocking by Meyer's (1961) standards. Site index values of Meyer for the general area range from 50 to 70 feet.

Treatments and Design

Six growing stock levels (GSLs) are being tested at this location. Originally, these GSLs were 30, 60, 80, 100, 120, and 140 square feet of basal area per acre where the Dq is 10 inches or more after thinning. Where Dq was less than 10 inches, the prescribed basal areas (PBA) for each GSL and Dq are tabulated in the study plan (Myers 1967). The relation of PBAs to GSLs and Dqs where Dq is less than 10 inches is,

$$PBA = 0.05454(GSL)(Dq^2)Exp(-0.1696\ Dq)\ . \qquad (1)$$

Equation (1) was determined by fitting the equation,

$$\log_e PBA = b_0 + b_1 \log_e(GSL) + b_2(GSL) + b_3 \log_e(Dq) + b_4(Dq)\ , \qquad (2)$$

to the tabulated values in Meyers (1967) by using step wise linear regression techniques. The coefficient for the (GSL) term was not significant ($p \leq 0.10$).

Plots and buffer strips were thinned to the prescribed levels initially (fall 1967) and after the second (fall 1977) and fourth periods (fall 1986) (figs. 1 and 2). After the fourth remeasurement (fall 1986), GSLs were changed to stand density index (SDI) values of 55, 110, 147, 183, 220, and 257. These SDI values are equivalent to the original GSLs when Dq is 10 inches. A wide range in Dqs had developed both within and between treatments by the end of the fourth period. The change in defining densities was necessary because the GSLs defined by equation (1) have no relation to any biological limit and cannot be interpreted as a constant relative level of competition across a range of stand diameters. The SDI values for ponderosa pine were determined by using,

$$SDI = (N)(Dq/10)^{1.77}\ , \qquad (3)$$

where N is live trees per acre and Dq is the quadratic mean diameter (DeMars and Barrett 1987). An exponent of 1.77 instead of 1.605 was used because -1.7653 was the slope of a least squares fit of $\log_e N$ as a function of $\log_e Dq$ for Meyer's (1961) original data (DeMars and Barrett 1987). Oliver and Powers (1978) also found a slope of -1.77 for a least squares fit of the same function for data collected in a survey of dense, natural, even-aged stands of ponderosa pine in northern California. The SDI for normally stocked stands in Meyer (1961) is 365 (DeMars and Barrett 1987).

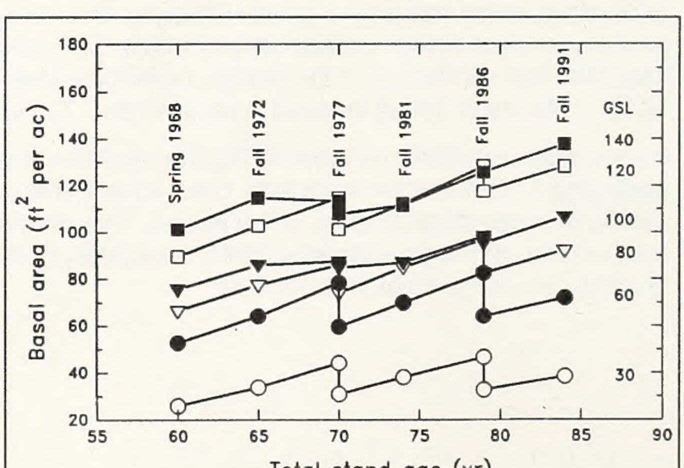

Figure 1—Live basal area (treatment means) in relation to total age and year for each GSL.

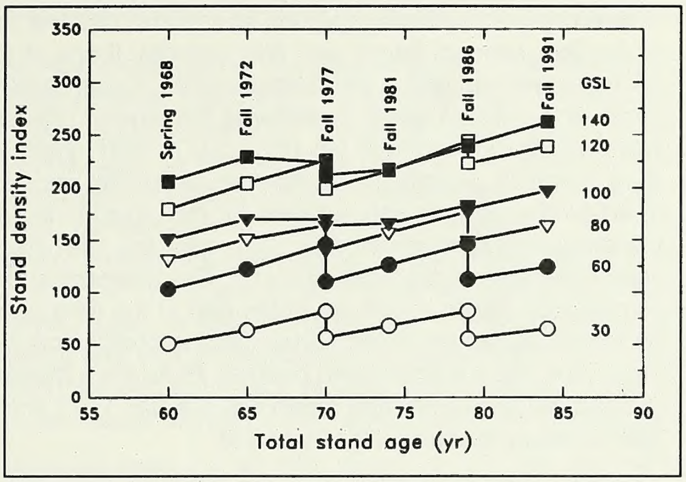

Figure 2—Stand density index of live trees (treatment means) in relation to total age and year for each GSL.

Each growing stock level was replicated three times. A randomized complete block design was used to place a complete replication on each of the three different soils. Replication three is about 3 miles from replication one, and replication two is about half way between replications one and three.

Installation and Measurements

Square plots 0.4 or 0.5 acre in size, with additional 33-foot buffer strips, were used. Buffer strips received the same treatments as did the associated plots. Stand openings prevented the use of larger plots. A pretreatment inventory of diameters at breast height (d.b.h.) was taken for each plot, and the plots and buffer strips were precommercially thinned in fall 1967. Thinning slash was lopped and scattered.

In spring 1968, each d.b.h. was measured to the nearest 0.1 inch, and 15 trees on each plot were selected for measuring with an optical dendrometer. Selection of these trees was made randomly at the beginning of the study within 1-inch diameter classes across the range of tree sizes. Stem volumes inside bark, including stump and tip, in cubic feet (V) were calculated for each of these selected trees by using equations from Grosenbaugh's (1964) STX program with a modification to describe bark thickness along the bole (Cochran 1976). Coefficients for the volume equation (Husch and others 1972),

$$\log_e V = a + b[\log_e(\text{d.b.h.})] \,, \qquad (4)$$

were computed for each plot, and plot volumes were then calculated from the measured diameters. Heights from the 15 trees measured with a dendrometer were used to determine coefficients in the equation (Curtis 1967),

$$\log_e H = a_1 + b_1/(\text{d.b.h.}) \,, \qquad (5)$$

for each plot. This equation was then used to estimate tree heights. Scribner board foot volumes (V1) were calculated for trees 8 inches and greater in diameter with a 5-inch or greater top diameter inside bark at 17 feet by using,

$$\text{Log}_e V1 = 0.9608 + 1.4667(\log_e V) - 0.1739(\log_e H) - 0.1700(\log_e \text{d.b.h.}) \,. \qquad (6)$$

Equation (6) ($R^2 = 0.99$, standard error = 0.10) was developed from 100 ponderosa pine trees ranging from 8 to 27 inches d.b.h. destructively sampled over a wide range of sites in Oregon and Washington during other studies.

These procedures were repeated after 5, 10, 19, and 24 growing seasons (the end of the first, second, fourth, and fifth periods). If one of the trees originally selected for measurement with a dendrometer died, it was replaced with a tree having the same or nearly the same diameter at the time of previous measurement. Periods one through five ended in fall 1972, 1977, 1981, 1986, and 1991, respectively (figs. 1 and 2). Equations for the start of the first period (spring 1968) were used to determine heights and volumes for the plots in fall 1967 before initial thinning. At the end of the third period (fall 1981, after the 14th growing season), diameters only were measured due to lack of funds. The intercept and slope values for the cubic volume and height equations at the end of the third period (fall 1981) were obtained by averaging values of the corresponding coefficients determined for each plot at the end of the second and fourth periods. Plots were thinned back to prescribed levels at the end of the second and fourth periods (fall 1977 and fall 1986 after the 10th and 19th growing seasons) (figs. 1 and 2).

Annual tree mortality (R_m) was calculated as a negative interest rate for each plot-period combination by using,

$$R_m = 1\text{-}(N2/N1)^{(1/n)} \qquad (7)$$

(Hamilton and Edwards 1976); where N1 and N2 are the number of live trees at the beginning and end, respectively, of each period and n is the period length in years.

Periodic annual increments (PAI, growth during each period divided by the number of growing seasons in the period) were calculated for gross and net basal area, gross and net cubic volume, and gross and net board foot volume. The PAIs of quadratic mean diameters and average heights also were determined for surviving trees. Mean annual gross and net basal area and volume growth (growth during the study divided by the number of growing seasons in the study) taking into account the thinnings after the second and fourth periods were calculated for the 24-year study. Volume yields (cumulative net yields), the live standing volume at a given time plus the live volume removed in any previous thinnings (including the initial thinning), were determined for each time of measurement. Mean annual volume increments (MAI, cumulative net yields divided by age) also were calculated. Yield, mean annual growth, and PAIs for board foot volumes include ingrowth. Mean annual growth rates of volume and basal area for the 24-year study were determined when possible for the 30, 60, 90, and 120 surviving trees per acre that had the largest diameters at the start of the study. Lower GSLs did not retain all these fixed numbers of trees initially or later as the study progressed. One GSL 30 plot had only 30 trees per acre at the end of the fifth period.

Site index values for these plots were determined with Barrett's (1978) method using the two tallest estimated heights per plot in fall 1991. Barrett's site index is the average height of the five tallest trees per acre when the stand age at breast height is 100 years. Meyer's site index is the height attained by a tree with a diameter equivalent to the mean diameter of the dominant and codominant trees at a total stand age of 100 years. The relation between Barrett's site index in feet (S) and Meyer's site index in feet (S1) is,

$$S = 37.735 + 0.9315(S1)\ . \qquad (8)$$

This relation was determined from the original plot data of Meyer.[1]

Analyses

Standard analyses of covariance or repeated measures (split-plot in time) analyses (SAS Institute 1988) with Barrett's site index as the covariate were used to test the following hypotheses: (1) There are no differences in tree mortality rates with GSL, period (age), or replication (a value of one was added to each mortality rate to avoid using zeros in the analysis of covariance). (2) There are no differences in PAIs with GSL, period (age), or replication. (3) There are no differences in mean annual gross or net growth of basal area or volume during the 24-year study with GSL or replication. (4) There are no differences in mean annual volume increments with GSL, period (age), or replication. (5) There are no differences in cumulative net volume yields with GSL or replication. (6) Mean annual growth of the 30 largest trees is not changed with replication or GSL. Site index was used as a covariate because site index values differed widely among plots within each replication.

Because there are six GSL levels, up to a fifth degree polynomial can be used to describe the relation between response and GSL. Results from other LOGS studies (Barrett 1983, Oliver and Edminster 1988, Ronco and others 1985) indicated that linear or second-degree polynomials would sufficiently describe this relation. Linear, quadratic, and lack-of-fit effects were therefore tested in both the standard analyses and the repeated measures analyses by using orthogonal polynomial methods. In the repeated measures analyses, linear, quadratic, and lack-of-fit terms also were tested for the time by GSL interaction. The unequal spacing between GSLs was taken into account in determining the coefficients used in these tests (Bliss 1970).

Regressions of the form,

$$\log_e PAI = c_0 + c_1 \log_e S + c_2 \log_e SDI + c_3 SDI + c_4 \log_e A + C_5 A \,, \qquad (9)$$

were used to relate gross PAIs of basal area and volume to Barrett's site index (S), midperiod SDIs, and total age at midperiod (A). Coefficients were determined for equation (9) by using the general linear models procedure (SAS Institute 1988) with combined data from all periods (90 observations) assuming independence of each observation. An equation similar to equation (9) was used by Curtis and Marshall (1986) for Douglas-fir except they used dummy variables for periods instead of age, and they did not include site index.

Results

At the start of the first period (spring 1968), basal areas ranged from 26 to 101 square feet per acre with corresponding volumes of 354 to 1,326 cubic feet per acre. Average tree sizes from the lowest to the highest densities ranged from a Dq of 7.5 inches and an average height of 39 feet to a Dq of 6.4 inches and an average height of 35 feet (table 1). Twenty-four years later, at the end of the fifth period (fall 1991), Dqs ranged from 14.1 inches at the lowest stocking level to 8.8 inches at the highest stocking levels. Corresponding average heights ranged from 63.5 to 50 feet. Average size of trees thinned at the end of the second and fourth periods (table 2) was smaller than the average size of the live trees, thereby resulting in an increase in mean diameter immediately after thinning.

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[1] Personal communication. 1988. Donald J. DeMars, research mensurationist, Juneau Forestry Sciences Laboratory, 2770 Sherwood Lane, Suite 2A, Juneau, AK 99801-8545.

Table 1—Average stand statistics over the 24-year study period

Assigned GSL[a]	Initial SDI[b]	Trees per acre	Mean[c] d.b.h.	Average height	Basal area	Volume	Volume, Scribner
			Inches	*Feet*	*Ft²/acre*	*Ft³/acre*	*Bd. ft./acre*
Live trees after initial thinning and mortality—fall 1967 and spring 1968							
30	51	86	7.5	39.0	25.9	354	374
60	103	165	7.7	39.2	52.8	684	810
80	131	233	7.3	37.5	66.5	897	902
100	151	290	6.9	37.0	75.6	994	832
120	180	386	6.5	36.6	89.5	1,171	653
140	206	455	6.4	34.6	101.2	1,328	898
Live trees at the start of the second period—fall 1972 and spring 1973							
30	64	86	8.5	41.7	33.7	515	1,010
60	122	165	8.5	41.5	64.2	958	2,068
80	151	233	7.9	40.1	77.5	1,126	1,990
100	170	290	7.4	39.0	86.0	1,228	1,659
120	204	386	7.0	39.2	102.7	1,450	1,452
140	229	455	6.8	38.2	114.7	1,643	1,718
Live trees at the end of the second period—fall 1977							
30	82	86	9.7	45.5	44.2	778	1,978
60	146	165	9.4	44.8	78.4	1,334	3,112
80	164	224	8.4	43.6	86.2	1,403	2,754
100	170	259	7.9	42.3	87.5	1,431	2,719
120	226	378	7.5	42.8	114.7	1,842	2,238
140	224	398	7.4	39.8	113.2	1,836	2,182
Live trees at the start of the third period after the second thinning—fall 1977 and spring 1978							
30	57	58	10.0	46.2	30.9	545	1,577
60	110	113	9.9	47.1	59.7	1,045	2,729
80	140	177	8.8	44.9	73.9	1,225	2,621
100	164	247	8.0	44.4	84.8	1,316	2,205
120	199	332	7.5	42.8	101.2	1,623	1,853
140	212	371	7.4	40.0	107.9	1,758	2,384
Live trees at the start of the fourth period—fall 1981 and spring 1982							
30	68	58	11.1	51.0	38.1	781	2,284
60	126	113	10.8	51.0	70.0	1,375	4,023
80	157	175	9.4	46.8	84.9	1,589	3,441
100	166	243	8.4	45.4	87.0	1,586	2,926
120	216	327	7.9	44.9	112.1	2,018	3,092
140	217	340	7.8	44.2	111.5	1,971	3,196

Table 1—Average stand statistics over the 24-year study period (continued)

Assigned GSL[a]	Initial SDI[b]	Trees per acre	Mean[c] d.b.h.	Average height	Basal area	Volume	Volume, Scribner
			Inches	*Feet*	*Ft²/acre*	*Ft³/acre*	*Bd. ft./acre*
Live trees at the end of the fourth period—fall 1986							
30	82	58	12.3	56.2	46.7	1,086	3,719
60	146	112	11.7	56.0	82.4	1,827	6,002
80	177	174	10.1	49.0	96.8	1,930	5,510
100	183	221	9.0	48.3	98.2	1,986	4,458
120	244	324	8.5	48.1	128.2	2,525	4,764
140	240	339	8.3	46.7	125.7	2,426	4,885
Live trees at the start of the fifth period after the third thinning—fall 1986 and spring 1987							
30	56	36	13.0	58.7	32.6	775	2,767
60	112	78	12.4	58.5	64.2	1,464	5,021
80	149	132	10.8	50.7	82.4	1,677	4,817
100	180	212	9.1	48.6	95.2	1,943	4,444
120	223	283	8.7	48.7	117.5	2,328	4,665
140	240	339	8.3	46.7	125.7	2,426	4,885
Live trees at the end of the fifth period—fall 1991							
30	65	36	14.1	63.5	38.4	950	3,700
60	124	76	13.3	62.7	72.0	1,790	6,473
80	164	130	11.5	55.4	92.3	2,034	6,524
100	197	211	9.6	51.7	106.7	2,228	5,453
120	239	283	9.1	51.7	128.2	2,612	6,149
140	262	337	8.8	50.0	137.7	2,767	6,198

[a] GSL = growing stock level.
[b] SDI = stand density index.
[c] Mean = quadratic mean.

Table 2—Stand statistics for trees removed in thinning after the first and fourth periods

Assigned GSL[a]	Trees per acre	Quadratic mean d.b.h.	Basal area	Cubic volume
		Inches	*Ft^2/acre*	*Ft^3/acre*
		First period		
30	28	9.4	13.4	233
60	52	8.2	18.7	288
80	47	7.1	12.2	178
100	12	6.4	2.7	39
120	46	7.5	13.4	219
140	27	5.8	5.3	78
		Fourth period		
30	22	11.0	14.0	311
60	34	9.9	18.2	363
80	42	7.8	14.1	253
100	9	7.3	3.0	43
120	41	6.6	10.6	198
140	0	0	0	0

[a] GSL = growing stock level.

Site Index Values and Initial Tree Age

Site index values (Barrett 1978) for the plots ranged from 76 to 103 feet with an average of 89 feet. These values might be low due to some suppression of height growth before the initial thinning. Site index values did not differ significantly ($p \leq 0.10$) with replication or GSL. Age at breast height for the plots was 46 years at the start of the study.

Mortality

Ten of the 18 plots experienced some mortality before the first growing season was over. Twenty-six trees were snapped off in winter 1967-68 or died of unknown causes, and 23 trees died after being attacked by the western pine engraver (*Ips pini* (Say)). This early mortality amounted to less than 0.4 percent of the live trees present at the end of the first growing season. Because these trees were lost before the start of the first growing season or early in the first growing period, calculations for this report were made assuming these trees died before establishment of the study.

After the first growing season, nearly all the mortality (table 3) was related to attacks by mountain pine beetles (*Dendroctonus ponderosae* Hopkins). Mortality rates differed ($p \leq 0.10$) with GSL and period (table 4). The significance ($p \leq 0.10$) of the period by GSL linear interaction term indicates that the relation of mortality to GSL differed with period. Mortality occurred for 31 of the 90 plot-period combinations and ranged from 2 to 115 trees per acre for these 31 instances. This range in loss corresponds to 0.4 to 30 percent of the trees, 0.5 to 29 percent of the basal area, and 0.4 to 36.5 percent of the cubic volume alive at the start of the period in which the mortality occurred. Examination of this mortality for each period in relation to stand density, tree size, trees per acre, and volume indicated that:

1. Mortality did not occur at the lowest GSL. Annual mortality rates above 1 percent did not occur when SDI values at the beginning of a period were below 140 (fig. 3). No mortality occurred when average tree spacing was 25 by 25 feet or greater.

2. Trees that died during any period were about the same size as the trees that lived. Ratios of mean diameters of trees that died on a given plot during each period divided by the mean diameter of the live trees on the plot at the start of the corresponding period averaged 0.98 and ranged from 0.7 to 1.3. This ratio did not seem related to stand density.

3. Even at SDIs higher than 140, there was no apparent correlation between stand density and mortality. Some high-density plots had no mortality during some periods (fig. 3), and one GSL 120 plot had no mortality during the 24-year period.

Periodic Annual Increments

Survivor PAIs for Dq decreased curvilinearly ($p \leq 0.10$) with increasing GSLs, decreasing greatly as GSLs differed from 60 to between 80 and 120 and then decreasing at a lower rate as a GSL of 140 was approached (table 4, fig. 4). Survivor height PAIs varied erratically, generally increasing curvilinearly with increasing GSLs in periods one and two, and generally decreasing curvilinearly with increasing GSLs in period four (table 4, fig. 5). Gross PAIs for basal area (fig. 6) and cubic volume increased (fig. 7) curvilinearly ($p \leq 0.10$) with increasing GSLs (table 4). Net PAIs for basal area (fig. 8) and volume (fig. 9) differed erratically. Board foot PAIs varied curvilinearly ($p \leq 0.10$), at first generally increasing and then decreasing with increasing GSLs (table 4, fig. 10).

All PAIs differed significantly ($p \leq 0.10$) with period. All PAIs except those for surviving heights generally at first increased and then decreased with increasing stand age (table 4, figs. 4-10). Rates of change in PAIs with GSL differed significantly ($p \leq 0.10$) among periods for net basal area and surviving heights only; although Dq PAIs tended to do so as indicated by a *p*-value of 0.1273 for the period x linear interaction (table 4).

Table 3—Average mortality rates by GSL and period

Assigned GSL[a]	Trees per acre	Quadratic mean d.b.h.	Basal area	Cubic volume
		Inches	*Ft²/acre*	*Ft³/acre*
		First period		
30	0	—	—	—
60	0	—	—	—
80	0	—	—	—
100	0	—	—	—
120	0	—	—	—
140	0	—	—	—
		Second period		
30	0	—	—	—
60	0	—	—	—
80	9	7.8	2.8	45.7
100	31	7.9	11.1	184.0
120	8	7.0	2.0	31.0
140	57	6.8	15.8	260.5
		Third period		
30	0	—	—	—
60	0	—	—	—
80	2	8.6	.8	12.3
100	22	8.6	8.0	129.1
120	6	7.7	1.9	30.8
140	31	6.9	8.0	119.5
		Fourth period		
30	0	—	—	—
60	.7	7.5	.2	9.6
80	.7	11.6	.5	10.1
100	3.3	8.9	1.45	26.8
120	2.5	6.0	.5	7.4
140	.7	6.4	.2	2.2
		Fifth period		
30	0	—	—	—
60	2	11.3	1.4	30.5
80	1.5	8.0	.5	9.0
100	1.3	19.4	.6	13.2
120	0	—	—	—
140	2.7	6.6	.6	6.1

[a] GSL = growing stock level.

Table 4—Probability of higher *F*-values for the repeated measures analyses of covariance of mortality rates and PAIs

Source	Df[b]	Mortality rate	Mean[c] d.b.h.	Average height	Basal area Gross	Basal area Net	Cubic volume Gross	Cubic volume Net	Scribner board feet Gross	Scribner board feet Net
		Probability of higher *F*-values								
			PAI[a]							
Block	2	0.3234	0.3072	0.1091	0.1539	0.2905	0.5584	0.8965	0.5965	0.5233
Regression (treatment vs. site index)	1	.4515	.1717	.0127	.0519	.4309	.0080	.0235	.0007	.0002
GSL:										
Linear	1	.0001	.0001	.5450	.0001	.5028	.0001	.0068	.1288	.2182
Quadratic	1	.9246	.0039	.0872	.0624	.0720	.0438	.0250	.0682	.0643
Lack of fit	3	.0008	.7229	.7800	.5658	.0087	.5830	.0475	.6338	.4445
Error	10									
Period (P)	4	.0372	.0003	.0569	.0073	.0116	.0001	.0008	.0001	.0001
P x GSL:										
Linear	4	.0751	.1273	.0070	.5713	.0038	.8352	.6710	.5391	.5602
Quadratic	4	.6940	.7491	.3327	.6864	.5937	.4040	.5472	.4123	.4336
Lack of fit	12	.3826	.4266	.7553	.7430	.1399	.4041	.2205	.2339	.5680
Error	48									
Error mean square:										
Whole plot		.000017	.0011	.0312	.1848	.4523	247.90	241.99	4,244.26	2,671.93
Subplot		.000027	.00048	.0648	.2312	.4905	217.16	315.94	3,817.91	4,094.43

[a] PAI = periodic annual increment.
[b] Df = degrees of freedom.
[c] Mean = quadratic mean.

Mean Annual Growth for 24 Years

Mean annual growth of gross basal area increased linearly ($p \leq 0.10$) with increasing GSLs (table 5, fig. 11). Mean annual growth of gross cubic volume increased curvilinearly ($p \leq 0.10$) with increasing GSLs (table 5) reaching a maximum at GSL 120 and then leveling off or decreasing (fig. 12). Mean annual growth of net basal area and cubic volume was erratic due to high rates of mortality in some of the plots at GSLs 100 to 140. Mean annual gross and net Scribner board foot growth (which includes ingrowth) varied curvilinearly ($p \leq 0.10$) with GSL increasing markedly from GSL 30 to GSL 60 and decreasing rapidly from GSL 120 to GSL 140 (fig. 13).

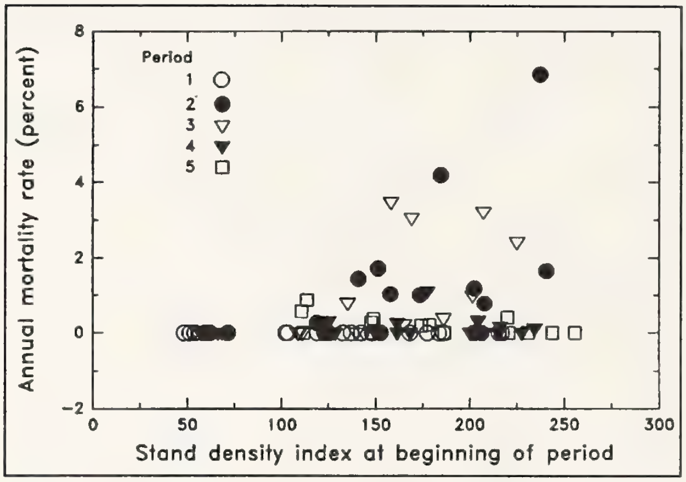

Figure 3—Relation of annual mortality rates to SDI at the start of the period for the 90 plot-period combinations.

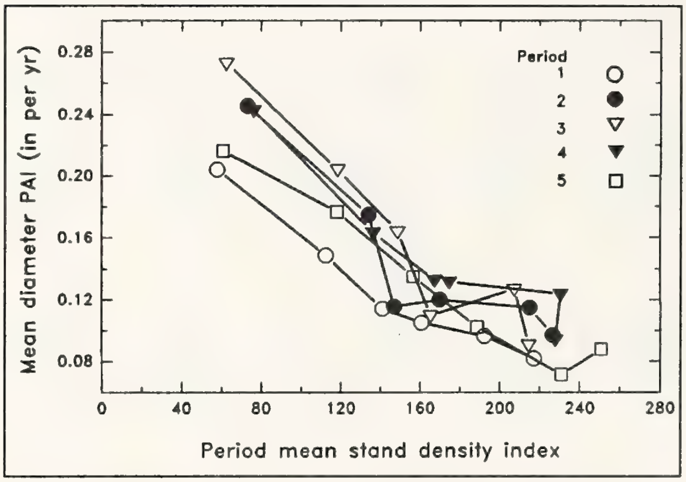

Figure 4—Relation of survivor PAIs for quadratic mean diameter to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

Yields

Cubic volume yield at a total stand age of 84 years (fall 1991) increased linearly ($p \leq 0.10$) with increasing GSLs (table 6, fig. 14). Corresponding Scribner board foot yield varied curvilinearly ($p \leq 0.10$) with GSLs increasing from GSL 30 to GSL 60 and then decreasing from GSL 120 to GSL 140 (table 6, fig. 15).

Text continues on page 18.

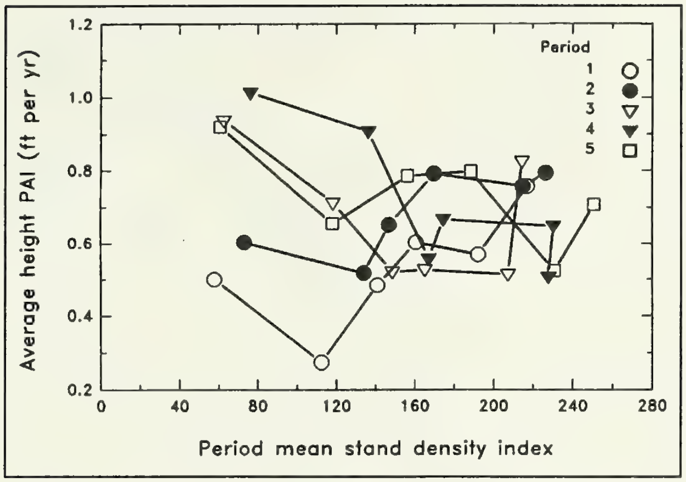

Figure 5—Relation of survivor PAIs for average height to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

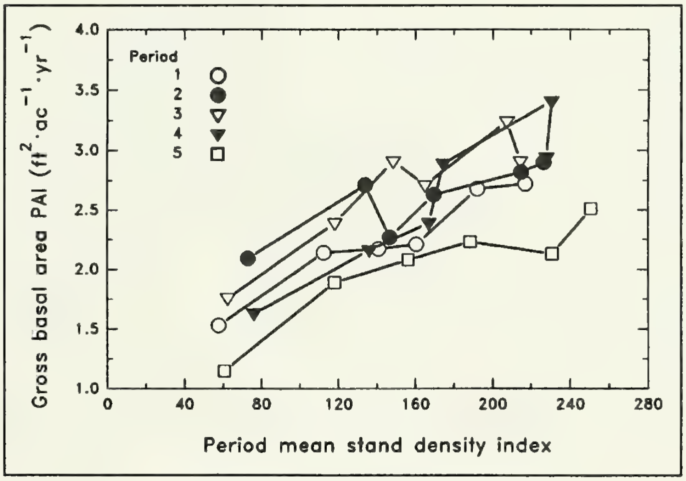

Figure 6—Relation of PAIs for gross basal area to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

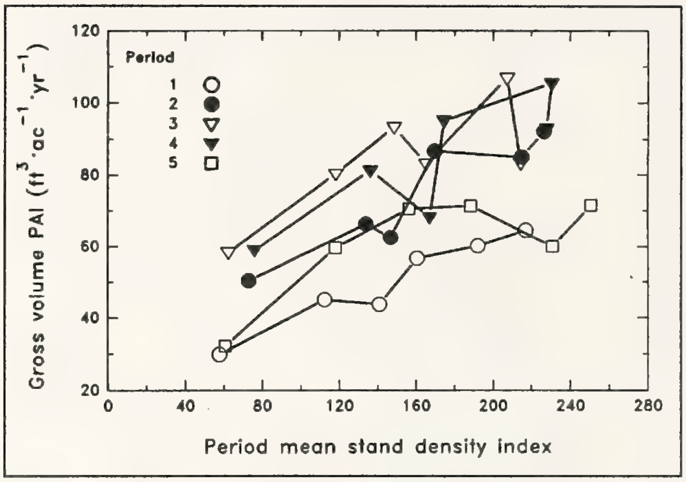

Figure 7—Relation of PAIs for gross cubic volume to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

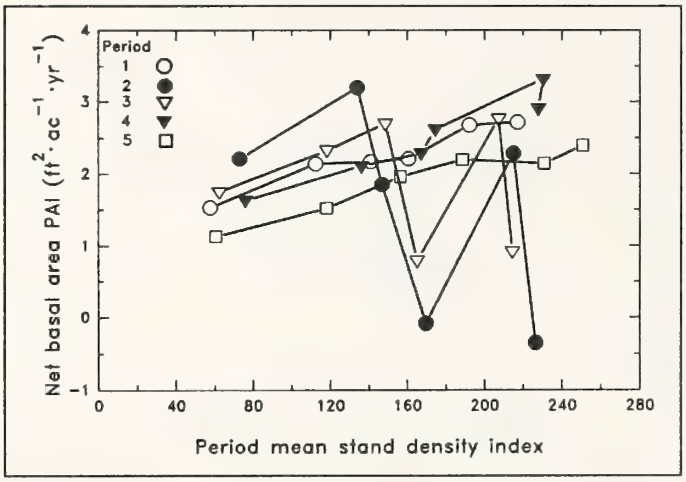

Figure 8—Relation of PAIs for net basal area to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

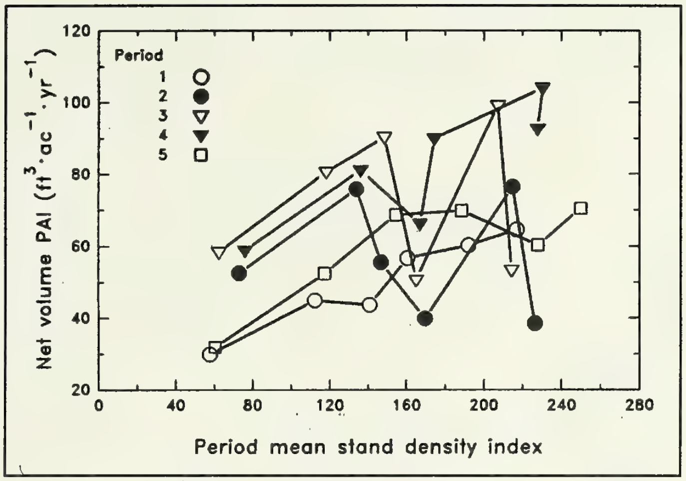

Figure 9—Relation of PAIs for net cubic volume to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

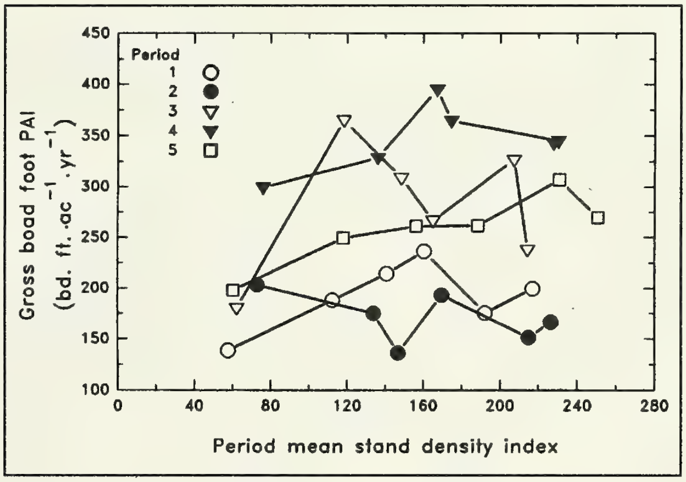

Figure 10—Relation of PAIs for gross Scribner board foot volume to period mean SDI for the five periods of study. Plotted points are adjusted means for GSLs 30, 60, 80, 100, 120, and 140.

Table 5—Probability of higher *F*-values for the analyses of covariance for mean annual growth of basal area and volume during the 24-year study

		Probability of higher *F*-values					
		Mean annual basal area growth		Mean annual cubic volume growth		Mean annual board foot growth	
Source	Degrees of freedom	Gross	Net	Gross	Net	Gross	Net
Block	2	0.3200	0.2595	0.1940	0.6830	0.5860	0.5604
Regression (treatment vs. site index)	1	.0008	.0198	.0006	.0063	.0006	.0002
GSL:							
Linear	1	.0001	.5163	.0001	.0044	.1277	.2283
Quadratic	1	.1498	.1096	.0771	.0453	.0730	.0675
Lack of fit	3	.4291	.0108	.4291	.0363	.7574	.5837
Error	9						
MSE[a]		.0412	.0954	33.40	38.73	28.484	23.285
CV%[b]		8.47	15.39	8.26	9.78	11.75	9.94

[a] MSE = mean square for error from the analysis of variance.
[b] CV% = the coefficient of variation.

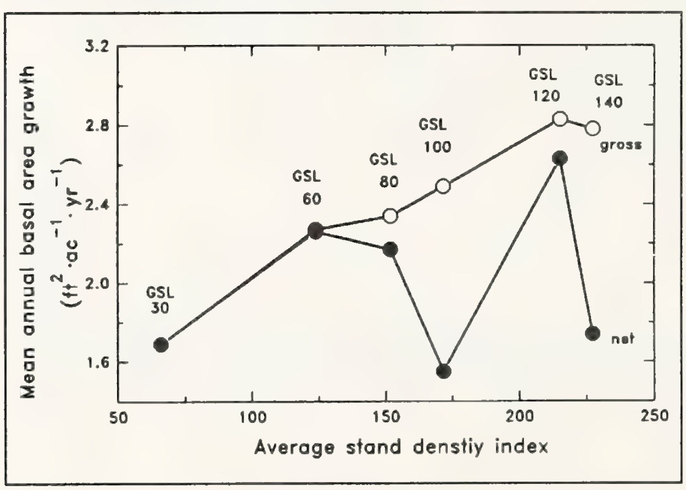

Figure 11—Mean annual basal area growth for the 24-year period (adjusted means) as a function of the average period mean SDIs for the five periods for each GSL.

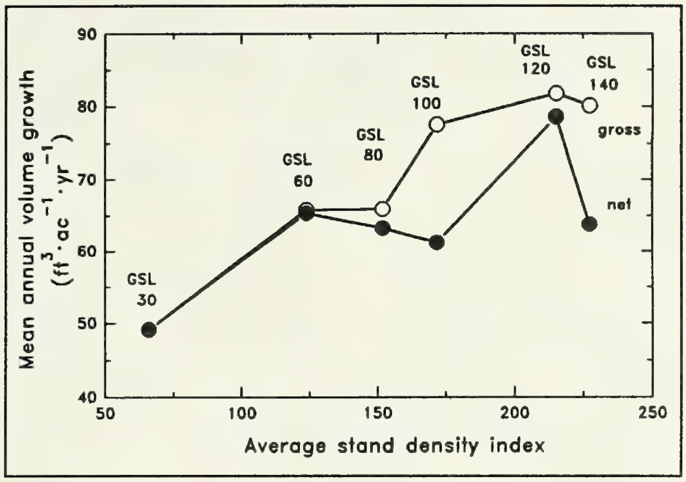

Figure 12—Mean annual cubic volume growth for the 24-year period (adjusted means) as a function of the average period mean SDIs for the five periods for each GSL.

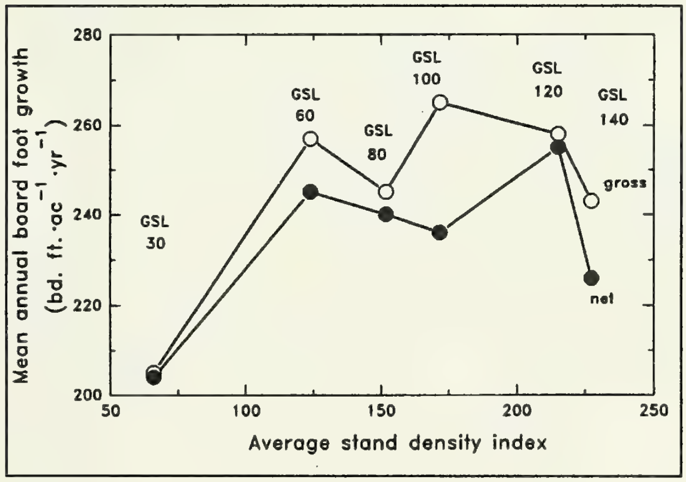

Figure 13—Mean annual board foot growth for the 24-year period (adjusted means) as a function of the average period mean SDIs for the five periods for each GSL.

Table 6—Probability of higher *F*-values for the analyses of variance of cumulative net volume yields in fall 1991 at a total stand age of 84 years

Source	Degrees of freedom	Probability of higher *F*-values	
		Cubic volume yield	Scribner bd. ft. yield
Block	2	0.8086	0.4401
Regression (treatment vs. site index)	1	.1353	.0002
GSL:			
Linear	1	.0246	.1446
Quadratic	1	.1411	.0321
Lack of fit	3	.4240	.8793
Error	9		
MSE[a]		14,5507.43	150,294
CV%[b]		10.6	23.0

[a] MSE = mean square for error from the analysis of variance.
[b] CV% = coefficient of variation.

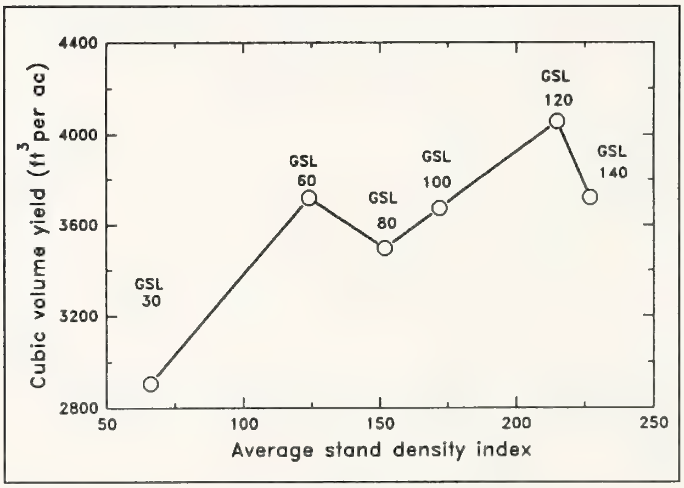

Figure 14—Cubic volume yield (adjusted means) as a function of the average period mean SDIs for the five periods for each GSL.

Mean Annual Increments

Mean annual increments of cubic volume increased linearly ($p \leq 0.10$) with GSL, but the rate of change of cubic volume MAI with GSL differed erratically with time as indicated by the significance ($p \leq 0.10$) of the lack of fit term for the period × GSL effect (table 7, fig. 16). Heavy mortality in GSLs 100 and 140 caused this erratic variation. Mean annual increments of board foot volume varied curvilinearly with GSL and differed erratically with time, increasing between GSL 30 and GSL 60 and then decreasing from GSL 120 to GSL 140 at stand ages of 74 and 84 years (table 7, fig. 17). Cubic volume MAIs increased with increasing stand age with the exception of cubic volume MAI for GSL 30 which shows no increase past age 79 years. Board foot MAIs increased with increasing stand age for all GSLs.

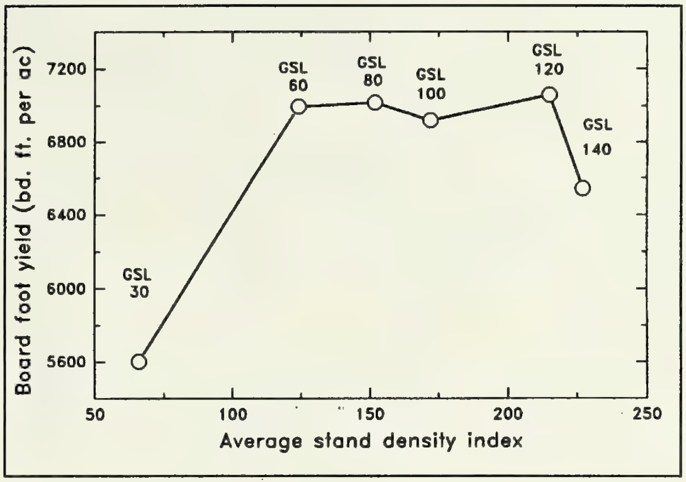

Figure 15—Board foot yield (adjusted means) for each GSL as a function of the average midperiod SDI for the five periods.

Table 7—Probability of higher *F*-values for the repeated measures analyses of variance of mean annual increments for cubic and Scribner board foot volumes

Source	Degrees of freedom	Probability of higher *F*-values for mean annual increments: Cubic volume	Scribner bd. ft. volume
Block	2	0.7159	0.4426
Regression (treatment vs. site index)	1	.2881	.0015
GSL:			
Linear	1	.0615	.3963
Quadratic	1	.2614	.0471
Lack of fit	3	.5103	.9174
Error	10		
Period (P)	4	.0001	.0001
P x GSL:			
Linear	4	.1747	.5882
Quadratic	4	.1792	.3577
Lack of fit	12	.0008	.0827
Error	48		
Error mean square:			
Whole plot		110.90	277.83
Subplot		1.27	29.49

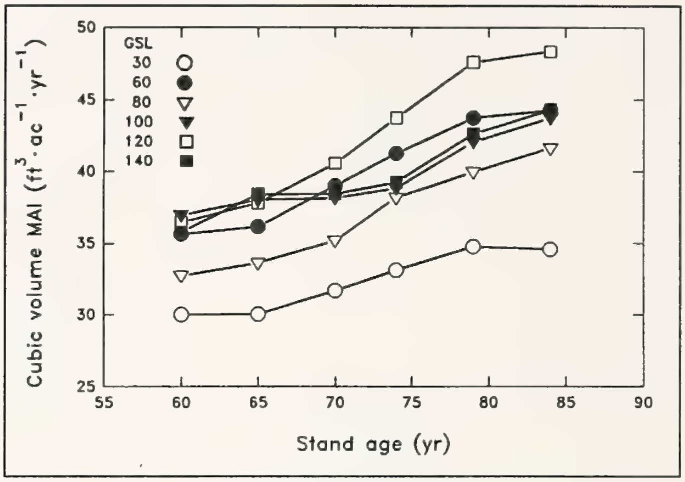

Figure 16—Cubic volume MAIs (adjusted means) for each GSL as a function of total stand age.

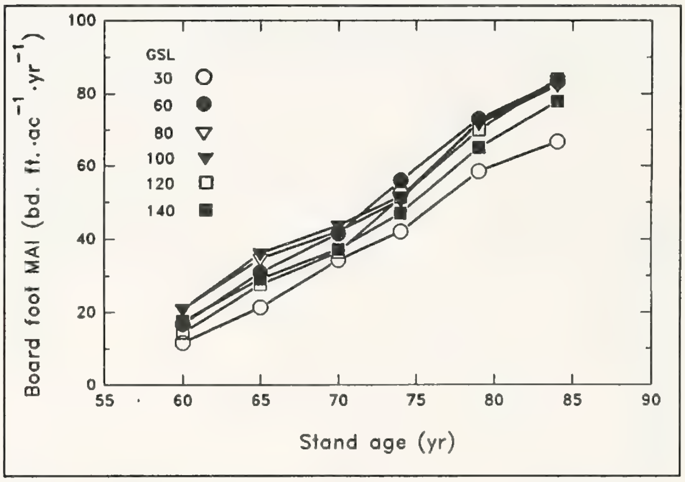

Figure 17—Board foot MAIs (adjusted means) for each GSL as a function of total stand age.

Growth of the 30 Largest Trees Per Acre

For the 24-year study, mean annual basal area growth of the 30 surviving trees with the largest diameters in spring 1968 decreased curvilinearly ($p \leq 0.10$) with increasing GSL (table 8, fig. 18). Mean annual cubic volume growth of these 30 largest trees decreased linearly ($p \leq 0.10$) with increasing GSL (table 8, fig. 19).

Regressions for Gross PAIs

The relation between gross PAIs for both basal area (fig. 20) and cubic volume (fig. 21) and SDI obtained by fitting equation (9) is clearly curvilinear within the range of SDIs examined. The regressions were performed to illustrate the functional relation between PAIs and the independent variables SDI, site index, and age. The regression analyses results (table 9) do not reflect the correct R^2s and probability levels because of the dependencies due to blocking and periods.

Table 8—Probability of higher *F*-values for the analyses of covariance of mean annual growth of volume and basal area during 24 years of study for the 30 surviving trees with the largest diameters in spring 1968

Source	Degrees of freedom	Probability of higher *F*-values: Mean annual basal area growth	Probability of higher *F*-values: Mean annual cubic volume growth
Block	2	0.0366	0.4475
Regression (treatment vs. site index)	1	.0434	.0075
GSL:			
Linear	1	.0001	.0003
Quadratic	1	.0975	.6503
Lack of fit	3	.9355	.7373
Error	9		
MSE[a]		1.88	80.3
CV%[b]		12.5	15.5

[a] MSE = mean square for error from the analysis of variance.
[b] CV% = coefficient of variation.

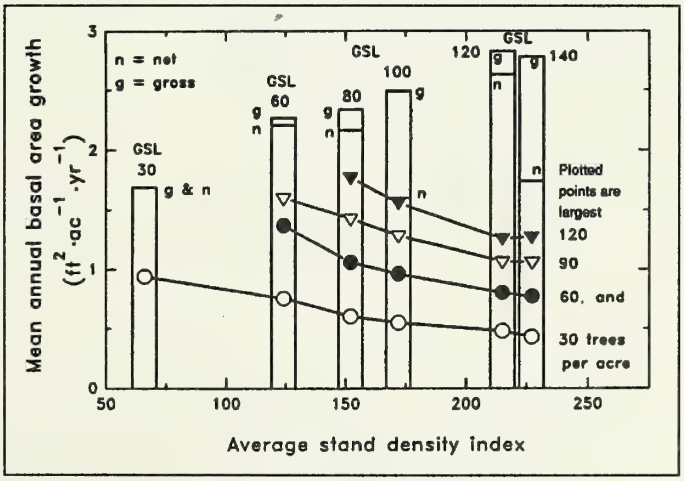

Figure 18—Relation of mean annual basal area growth (adjusted means) of all trees for each GSL and of the 30, 60, 90, and 120 trees per acre with the largest diameters at the start of the study to the average period mean SDI for each of the five periods.

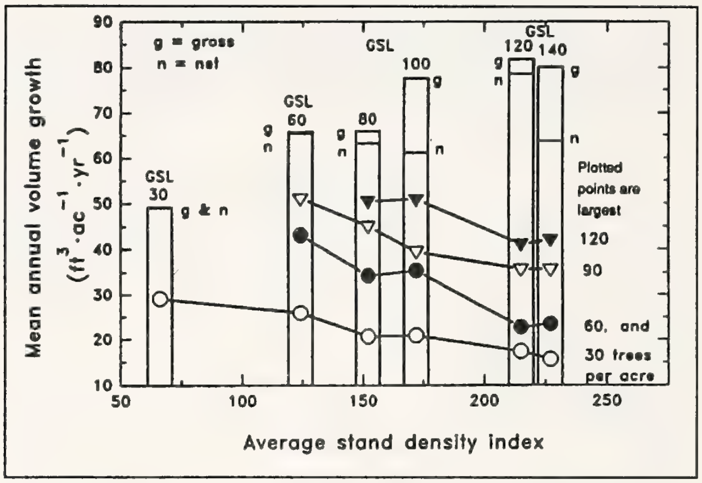

Figure 19—Relation of mean annual volume growth (adjusted means) of all trees for each GSL and of the 30, 60, 90, and 120 trees per acre with the largest diameters at the start of the study to the average period mean SDI for each of the five periods.

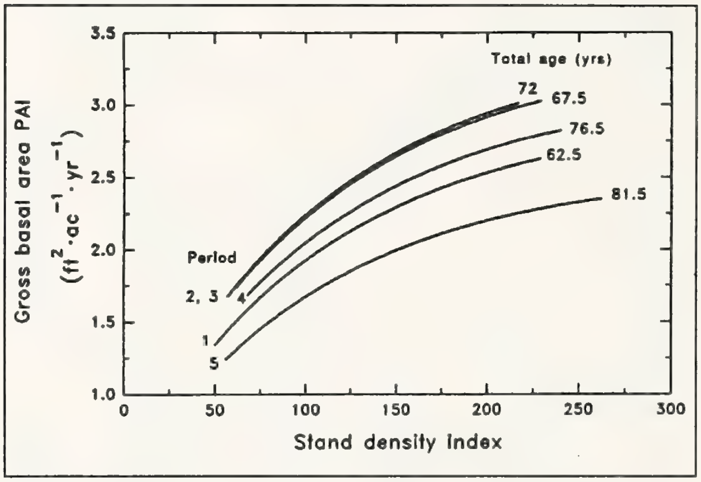

Figure 20—Gross basal area PAI as a function of SDI and total age using the coefficients in table 9 with a value of 90 for site index.

Discussion and Conclusions

High rates of mortality for GSLs 100 and 140 during period two (1972-77) and period three (1978-81) reduced the differences in stocking between GSLs 80 and 100 and between GSLs 100 and 140 for two of the five study periods (figs. 1 and 2). Although clear differences between all stocking levels did not exist for all periods, the study still supplies valuable information. Mortality was higher in this study than for the ponderosa pine levels-of-growing-stock studies in central Oregon (Barrett 1983), northern Arizona (Ronco and others 1985, Schubert 1971), or California (Oliver 1979). At these other ponderosa pine levels-of-growing-stock sites, curvilinearly decreasing PAIs for mean diameter and curvilinearly increasing net PAIs of basal area and volume with increasing stand densities occurred (Edminster 1988, Oliver and Edminster 1988). Similar results have been found in Douglas-fir levels-of-growing-stock studies (Curtis and Marshall 1986) where growing stock levels have been defined differently.

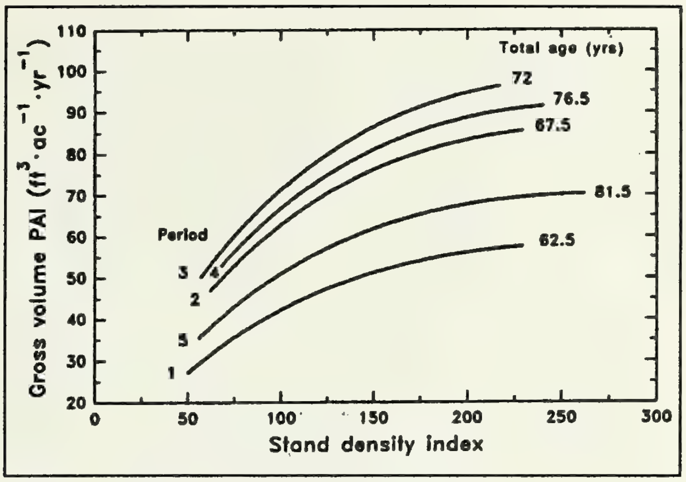

Figure 21—Gross cubic volume PAI as a function of SDI and total age using the coefficients in table 9 with a value of 90 for site index.

Table 9—Coefficients from linear regression analyses for equation (9),[a] assuming independence of all values and probabilities of greater absolute values of T for the hypothesis that the coefficient equals 0

	Gross periodic annual increment			
Coefficient	Basal area	p > ITI	Volume	p > ITI
c_0	–85.2583	0.0001	–166.8643	0.0001
c_1	.3779	.1631	1.5860	.0001
c_2	.6511	.0033	.8687	.0006
c_3	–.0018	.2766	–.0032	.0873
c_4	25.0928	.0001	48.7952	.0001
c_5	–.3579	.0001	–.6718	.0001
R^2	.59		.69	

[a] $\log_e PAI = c_0 + c_1 \log_e S + c_2 \log_e SDI + c_3 SDI + c_4 \log_e A + c_5 A$.

Several factors in addition to site index and stocking levels influenced growth rates in this study. Differences in adjusted means of MAIs for GSLs 30 and 80 (fig. 16) at the start of the study (stand age 60 years) indicate possible differences in growing conditions among some of the treatments not explained by site index. As the study progressed, stocking levels at the higher densities were altered on some plots by heavy mortality that occurred in clumps. A given stand measure of density for a plot with an uneven distribution of live trees may be a poor index to the growing space available to individual trees on the plot. In addition, there tends to be a lot of climatic variation between 5-year measurement periods in the intermountain West, and the relation of growth to density may differ with available soil water. During periods of low precipitation, growth of bole wood may be reduced more at higher densities, on south and west aspects, and on steep slopes where soil water is more limiting as a higher proportion of the carbon produced is directed to root systems.

The results of this study and of other levels-of-growing-stock and spacing studies in ponderosa pine indicate that stand growth, individual tree growth, and mortality, particularly from mountain pine beetle, all need to be considered when prescribing stand densities. High stand densities will produce the most gross cubic volume, but mortality may be severe, and individual tree sizes will be lower than in stands managed at lower densities. The larger tree sizes in stands of lower densities result in more board foot volume per tree and may result in more board foot volume per acre. On some sites, rapid development of the biggest and best trees may be a management goal, and the influence of small trees on the growth of larger trees in the stand should be considered. The mean annual cubic volume growth of the 60 largest trees for GSL 60 was 43 $ft^3 \cdot acre^{-1} \cdot year^{-1}$ (least square mean), 53 percent of the mean annual gross cubic volume growth of 81 $ft^3 \cdot acre^{-1} \cdot year^{-1}$ (least square mean) attained by GSL 120 (fig. 19) which had an average of 243 trees per acre at the end of the 24-year period. These results confirm other findings (Barrett 1963, 1983; Cochran and Barrett 1993) that competition from smaller trees reduces the growth of larger trees in even-aged ponderosa pine stands. Responses to proposed plans for the Malheur (USDA 1990a) and Deschutes National Forests (USDA 1990b) indicate that the public wishes to see trees larger than 18 inches in future ponderosa pine forests. Thinning from below to low densities would speed the development of large trees in second-growth stands.

Many practicing foresters and researchers have observed that mortality due to mountain pine beetle can be a serious problem in even-aged ponderosa pine stands less than 20 inches in diameter (Barrett 1979). The relation of mortality caused by mountain pine beetle and stand and tree characteristics is unclear. Tree size, spacing, tree vigor, and other factors seem to be involved (Mitchell and Preisler 1991). Mortality in this study occurred at densities even lower than the densities recommended for managed stands by Cochran (1992) but began at the upper density recommended by Barrett (1979) for sites V (Meyer 1961) and lower. Results from a nearby spacing study (Cochran and Barrett 1993) indicate that precommercial thinning in ponderosa pine should have a leave spacing of at least 18 by 18 feet. Results here indicate that once stands reach commercial size, thinning to maintain low stand densities will be necessary to reduce the probability of serious problems with mountain pine beetles and perhaps western pine beetles (*Dendroctonus brevicomis* LeConte).

The average site index value for the plots in this study is 90 feet (Barrett 1978) or 56 feet (Meyer 1961). Meyer (1961, table 21) shows cubic volume MAIs for this site culminating at age 60 years. The MAIs for this study show no signs of culminating at 84 years except for cubic volume MAI at the lowest stocking level (figs. 16 and 17). The National Forest Management Act of 1976 (Public Law 94-588) specifies the approximate age of culmination as the rotation age. Thinning delays culmination of total cubic volume growth (Curtis 1994). By reducing mortality and increasing diameter growth rates, stocking control could considerably increase rotation ages, individual tree sizes, and net yields of cubic and board foot volumes.

The desired future condition of ponderosa pine stands on National Forest lands has yet to be decided. Ponderosa pine is a long-lived species that responds to increased growing space even at old ages. A management strategy that produces trees 20 inches in diameter early, and includes repeated commercial thinnings over long rotations should both reduce mortality and enhance visual values. This strategy will not capture all the potential cubic volume production. The loss in cubic volume production should be acceptable, however, when board foot volumes, the social and monetary values associated with large trees, and the probability of avoiding severe mortality are considered.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 mile = 1.609 kilometers
1 acre = 0.4047 hectare
1 tree per acre = 2.47 trees per hectare
1 square foot = 0.09290 square meter
1 square foot per acre = 0.2296 square meter per hectare
1 cubic foot per acre = 0.06997 cubic meter per hectare

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Growth and mortality in a ponderosa pine (*Pinus ponderosa* Dougl. ex Loud.) stand were investigated for 24 years. High mortality rates from mountain pine beetle (*Dendroctonus ponderosae* Hopkins) occurred on some plots where values for stand density index exceeded 140. Periodic annual increments for quadratic mean diameters decreased curvilinearly as stand density increased, whereas periodic annual increments of gross basal area and gross cubic volume increased curvilinearly with increasing stand density. Cubic volume yield at a stand age of 84 years increased linearly with increasing density. Mean annual increments of board foot volume increased with time and show no signs of leveling off at a stand age of 84 years. Mean annual basal area and volume growth of the 30 largest trees per acre decreased with increasing levels of stand density. Ponderosa pine on low sites should be managed at low stand densities to avoid problems with mountain pine beetle and to produce large trees in a reasonable time period. Long rotations are probably possible for this species.

Keywords: Growth, mortality, mountain pine beetle, ponderosa pine, Blue Mountains (Oregon), forest health, thinning.

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